Ductility of ZIRLO™ Cladding After High Temperature Oxidation in Steam

Westinghouse Non-proprietary Class 3

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Zircaloy Ductility after High Temperature Oxidation in Steam

- Ductility measurements on Zircaloy oxidized in high temperature steam were used to establish cladding embrittlement criteria of 10 CFR 50.46
  - Peak Cladding Temperature no greater than 2200F
  - Equivalent Cladding Reacted (ECR) no greater than 17%
- Testing consisted of quench tests from temperature and ring compression tests of quenched specimens
  - Ring Compression Tests conducted on Zircaloy-4
  - Quench Tests of Zircaloy-2 and Zircaloy-4
- The purpose of the criteria is to ensure the cladding would remain sufficiently intact to assure an easily coolable geometry

Results of Tests on Alloy E110 Oxidized in High Temperature Steam (Bohmert, Kerntechnik 57)

- ECR to cause complete embrittlement is about 1/3 the value for Zircaloy-4
- A number of physical differences between the oxide layers of E110 and Zircaloy-4 were observed
  - E110 displayed a heterogeneous appearance of the oxide scale
  - E110 formed multi layer oxide layers that tend to flake
  - The two oxide layers of the E110 were frequently separated by cracks
  - Zircaloy-4 always had a glossy black firmly adherent single layer relatively free from mechanical failures
  - E110 showed low hydrogen uptake only if firmly adherent crackless oxide layers were formed
- High temperature steam oxidation tests of ZIRLO™ and Zircaloy-4 produce similar shiny black adherent oxide layers

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ZIRLO™ and E110 Are Not Equivalent

- Both alloys contain 1% niobium
- ZIRLO™ also contains
  - Sn
  - O
  - Fe
- Sn and oxygen are alpha phase stabilizers and raise the transition temperature relative to Zr-Nb binary alloys.
- The alpha-beta transition temperature of ZIRLO is near Zircaloy-4 and significantly higher than the Zr-Nb binary alloy temperature.
- There are significant differences in the oxide layer structure reported for the E110 alloy and those observed for either ZIRLO™ or Zircaloy-4

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Information Supplied for ZIRLO™ Licensing

- Testing of ZIRLO™ was performed to obtain data on the following areas
  - Material mechanical properties, density, thermal expansion, thermal conductivity, specific heat, phase changes,high temperature creep, high temperature oxidation, and rod burst characteristics.
- Other than phase change characteristics, the properties are essentially equivalent to those of Zircaloy-4
- It was argued that because of the close similarity to Zircaloy-4, the17% ECR criterion continued to apply
- The NRC agreed that the 17% criterion for zircaloy also applied to ZIRLO™ and 10 CFR 50.46 was ammended to state that the acceptance criteria applied to ZIRLO™

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Items for Discussion

- Background on Current issue
- Discussion of Alloy E110 vs ZIRLO
- Licensing History of ZIRLO
- Basis of 17% ECR and 2200 F PCT criteria for Zircaloy-4
- Testing Issues
- Criteria for Future Alloys

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- Summary of NRC memoranda
- Comments by G. Hache comparing Zr-1%Nb high temperature steam oxidation tothat of Zr-4
- Framatome comments on M5 versus E110
  - Conducted Ring Compression Tests similar to those of Böhmert
  - Non-embrittlement criterion for 17% of ECR easily verified with M5
  - M5 doesn't react the same way as E110

Review of Böhmert's papers

- Substantially different oxide layer characteristics for E110 and Zircaloy-4
  - E110 Zr-1%Nb specimens display a very heterogeneous appearance of the oxide scales. At an early stage multilayer oxide scales are formed which tend to flake.
  - Two layers of oxide form on E110 Zr-1%Nb that are frequently separated by cracks.
  - Zr-4 always has a glossy black firmly adherent single layer relatively free from mechanical failures.
  - Hydrogen uptake for Zircaloy-4 is low for all temperatures and times.
  - Hydrogen uptake for E110 Zr-1%Nb is only low if adherent, glassy black oxide layers have been formed.

Review of Böhmert's papers (cont.)

- E110 Zr-1%Nb is more susceptible to embrittlement than Zr-4 because of higher hydrogen absorption, higher oxygen absorption and a more homogeneous distribution of the oxygen in the matrix of Zr-1%Nb.
- The Zr-Nb-O system tends to a decomposition where Nb is enriched in the beta phase and oxygen is enriched in the alpha phase. This generates an irregular boundary between the alpha and beta layers that allows oxygen to be quickly absorbed in the beta phase.
- ECR was based on measured weight gains, not Baker-Just Equation

ZIRLO™ and E110 Are Not Equivalent

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Differences between Zr-4 and ZR-1%Nb reported by Böhmert may not apply to ZIRLO™ and Zr-4

- High temperature steam oxidation tests of ZIRLO™ and Zircaloy-4 show that they have similar oxide layer appearances with black shiny adherent layers.
- Sn and oxygen are alpha phase stabilizers and raise the transition temperature relative to Zr-Nb binary alloys.
- The alpha-beta transition temperature of ZIRLO™ is near Zircaloy-4 and significantly higher than the Zr-Nb binary alloy temperature.
- There are significant differences in the oxide layer structure reported for the E110 alloy and those observed for either ZIRLO™ or Zircaloy-4

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Review of the basis for the 17% ECR Criterion

- Based on ORNL Ring Compression tests of Zircaloy-4 and on quench tests for Zircaloy-2 and Zircaloy-4.
- Primary emphasis was on ring compression tests and quench tests were viewed as confirmatory
- Basis of selecting 17% ECR and 2200 F PCT was that some cladding ductility would exist after completion of the LOCA.
- The basis of the criterion was to maintain a coolable geometry during the LOCA.

Tests Used to License Various Alloys

• Zr-4	Ring Compression Tests, Quench Tests
• Zr-2	Quench Tests
• ZIRLO™	Similarity to Zr-4
• M5	Quench Tests
• Duplex D4	Quench Tests (Proposed)

Tests Being Proposed in the Industry

- Integral Tests
  - Heat Up
  - Steam Cooling
  - Quench
  - Simultaneous Mechanical Loading

- Constrained Quench Tests

- Material Property Tests (Modified Hobson Test)

Only Current "Standard" is Hobson Test

- Oxidation in Steam in Temperature range of 1700F to 2200F
- Instantaneous Quench from Peak temperature
- Slow Ring Compression Test to determine Nil Ductility
- ECR Calculated from Baker-Just Equation

Issues Associated with Revisions to Hobson Tests

- Heat-Up Rates
- Cooling rates prior to quench
- Temperature at which quench performed
- Mechanical testing method to determine ductilty
- Use of Baker-Just equation versus alternatives

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Standards are needed to Qualify New Alloys

- LOCA qualification will be a part of the alloy selection process along with other criteria.
  - Corrosion, growth, creep, hydrogen absorption, wear characteristics, burst characteristics, ...
- LOCA criteria should be realistic and not result in unnecessary elimination of otherwise superior alloys
- Requirements must be known in advance of material selection.